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Ultrasonic analysis of tungsten monoblock divertor mock-ups after high heat flux test

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In this paper, a comparison is presented among the ultrasonic measures of different W-monoblock mock-ups following high heat flux tests. The DEMO reference solution for the divertor targets (ITER-like) is compared with two other concepts, in which the interlayer between monoblocks and tube has been engineered to increase the performance of the component (Thermal Break Interlayer, Thin Graded Interlayer). Ultrasonic measurements have been performed at the depths of interest. The reflected signal amplitude and time of flight at defined depths are used to determine the shape and entity of the defect, when present. For each concept, the most frequently observed defects due to thermal loading are then identified. Preliminary post-mortem analysis confirms the results from the ultrasonic tests, proving the defect imaging capability of such non-destructive technique for advanced W-monoblock concepts.

Keywords: ultrasonic testing, non-destructive analysis, high heat flux, functionally graded interlayer, thermal break.

1. Introduction

In a fusion reactor, heat exhaust is one of the most challenging engineering issues, also due to the high heat flux (HHF) expected on the divertor targets. For DEMO, loads from 10 MW m^{-2} , for quasi-stationary operation, to $17 - 21 \text{ MW m}^{-2}$, when slow transient events occur, are predicted locally in the narrow region near the strike point [1]. Among the different layouts, the tungsten (W) monoblock design represents one of the most suitable technological solutions for plasma facing components, since it has already met the present ITER design requirements [2]. However, further research is required to investigate improved solutions able both to operate at DEMO conditions and to increase the expected lifetime of the component. In this context, new water-cooled divertor concepts are being developed as part of the research activity carried out by the EUROfusion Consortium. Therefore, several W monoblock mock-ups with innovative design have been manufactured by the involved partners, and subsequently tested with DEMO relevant cyclic heat loading in the HHF test facility GLADIS at IPP Garching [3]. Among others, two concepts, namely Thermal Break Interlayer (TBI) and Thin Graded Interlayer (TGI), have been developed and compared to the baseline reference of water-cooled divertor targets (ITER-like, IL). In the TBI concept [4], being developed at CCFE, the copper interlayer presents 6 radial spokes at the HHF side, as well as an additional groove on the low flux side at the axis of symmetry. In this way, the interlayer acts as a thermal barrier that helps the repartition, around the circumference of the pipe, of the heat flux that would otherwise intensify on the plasma-facing side of the heat sink. On the plasma side, the W block is divided in two halves in order to decrease the stress inside the armor during cycled loading. The TGI

is a concept developed at CEA Cadarache, where a solid W block is bonded to the CuCrZr tube using a graded interlayer where the concentration varies in $25 \mu\text{m}$ from 0% W (100 % Cu) to 100% W (0% Cu) [5]. The aim of the concept is to reduce both the amount of copper used, since it is a material prone to embrittlement due to fast neutron, and the thermal resistance of the component, by minimizing the heat conduction path. After the HHF test campaign it is crucial to assess the integrity of each mock-up and to identify the critical features of each target concept. For this purpose, ultrasonic test (UT) was performed at ENEA Frascati on all the mock-ups (6 IL, 4 TGI, 6 TBI), both before and after the HHF tests, in order to observe the formation of new defects as well as the evolution of pre-existing ones. UT was demonstrated to be able to detect defects and their location inside IL components with good accuracy [6]. However, the UT capability of detecting defects for innovative concepts is still to be confirmed. Compared to other non-destructive techniques, UT is particularly appropriate to test W monoblock mock-ups due to the opacity of W to X-rays, as well as the density and homogeneity of both W and CuCrZr, which result in clear transmitted pressure signals. The UT system used allows a direct imaging of the defects inside the component with a resolution of $500 \mu\text{m}$. In this paper, we present a comparison between ultrasonic scans, performed after the HHF test campaign, of three representative mock-ups of the studied concepts: IL, TBI and TGI. A comparison with preliminary metallographic images is performed in order to validate UT conclusions.

2. Materials and methods

2.1 Description of the mock-ups

Block dimensions as well as inner and outer diameter of the heat sink pipe for all concepts are reported in fig. 1.

All monoblocks have 4 mm of thickness along the z-axis for all layouts. A swirled tape is also fixed inside the pipe for all samples. The IL mock-up, manufactured by ENEA Frascati, consists of 12 blocks which are joined to the CuCrZr tube by means of Hot Radial Pressing (HRP; 600 °C, 50 MPa, 2 h) [7]. This concept provides a pure Cu interlayer of 0.5 mm thickness, which has been casted on the block. The mock-up with TGI is made of 10 blocks and is realized by CEA Cadarache. The interlayer has a thickness of 25 μm and is obtained through PVD. The deposit was performed inside the bore hole of the W monoblock, which is then joined to the CuCrZr pipe through Hot Isostatic Pressing (HIP; 950 °C, 120 MPa, 2 h). Thermal aging has been applied on the mock-up (475 °C, 3 h). The component with the TBI has 10 blocks and is fabricated by CCFE using a two-stage vacuum braze process. First, a pure copper sleeve is brazed on the CuCrZr tube, providing the interlayer material. Then the copper is machined, obtaining the structured interlayer geometry. The W blocks, provided with a thin casted Cu layer into the central bore, are then bonded to the first assemble through a second Cu-to-Cu brazing process (1000 °C). A precipitation hardening cycle is applied (475 °C, 2 h). The overall TBI thickness is 2 mm.

2.2 HHF testing

The HHF tests were performed at the neutral beam facility GLADIS at IPP Garching. The first step of the test procedure consists in an initial screening from 6 to 20 (or 25) MWm^{-2} and 100 cycles at 10 MWm^{-2} . The coolant inlet condition is 20 °C, 10 bar and 12 m/s. The second step of the HHF tests is conducted at DEMO relevant water conditions: 130 °C, 40 bar, 16 m/s. This section starts with an additional screening up to 20 MWm^{-2} , and ends with the thermal fatigue test up to 500 cycles at 20 MWm^{-2} . Each beam pulse lasts 10 s, time interval in which the loaded sample reaches the thermal equilibrium.

2.3 Ultrasonic test

UT was performed at the laboratories of ENEA Frascati. The method used was a pulse-echo water gap technique. The test is conducted by inserting an ultrasonic pulser/receiver probe inside the CuCrZr pipe with water fill. A handling system with two degrees of freedom, one translation and one rotation, operates the probe along the whole sample. The piezoelectric crystal inside the probes has a diameter of about 3 mm and works at frequencies of about 15 MHz. The probes are cylindrically shaped with the crystal placed laterally, normal to the radial direction of the component. In order to identify the defects due to the HHF tests, the ultrasonic scans are compared to the ones performed on the same samples before the thermal

fatigue campaign. The C-scan resolution is the same for the measurements performed before and after HHF tests, and is of 0.08 mm on the direction parallel to the axis of the pipe and 1° for the circumferential coordinate.

3. Results

Three types of result representations are reported. The first map (C-scan) reports, for each pixel, the maximum on a determined window of time of flight (ΔTOF), of the amplitude of the measured pressure signal at that position of the probe. The second (D-scan) reports, in the same ΔTOF , the time of flight (TOF) at which said maximum appears. All TOF are reported as millimetres, for an easier read of the depth information, by factoring in the velocity of sound inside copper (5000 m/s). The origin time is the time when we detect the signal from the water/ CuCrZr interface (0 mm = inner surface of the pipe). The third representation (B-scan) reports the amplitude of the pressure signal as a function of TOF and it is plotted for an arbitrary span of angular coordinates at a fixed position along the pipe axis.

The ultrasonic results of the IL sample are shown in Fig. 2. The maps are reported for a ΔTOF around the bonding interface between CuCrZr pipe and the Cu interlayer (HRP interface), since no defects were detected at other interfaces. The outer surface of the naked tube appears as red lateral bands in the C-scan, and it is detected, as expected, at $TOF = 1.50$ mm (red colour in D-scan). In the D-scan, we observe also red spots inside the sample, which correspond to defects at the HRP interface. These indications are manufacturing defects and therefore were present before the HHF tests. Their dimension did not increase after the thermal fatigue campaign. From the C-scan, we detect small debonding at the sides of all monoblocks that appeared at the HHF region. Their maximum extension along the pipe axis is of 1.3 mm on average, shared between blocks. This indication is detected only after the thermal cycles and it is located at the HRP interface. In the C-scan, we observe also the appearance of small pores in the HHF region of the sample. A better view of this indication is available in the D-scan where such porosity appears as white spots, which means that the pores are located inside the Cu interlayer (~ 0.3 mm from HRP interface). Preliminary post-mortem analysis confirms UT result (Fig. 5), where debonding at ends of blocks and porosity are observed.

No defects are detected in the mock-up with TGI both inside W and at the HIP interface, which did not show any debonding or failure of the graded material as reported in figure 3(right). The TGI in fact did not affect the detection

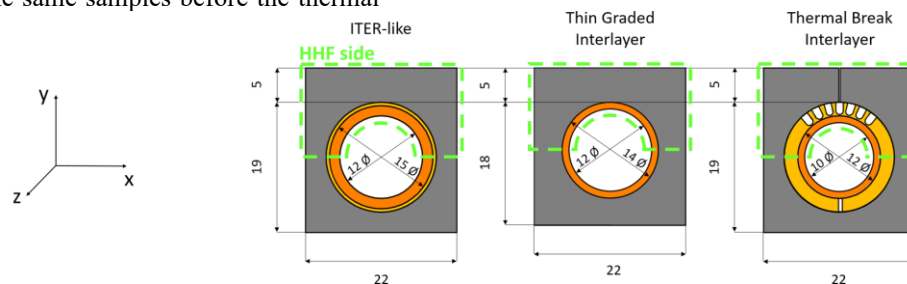


Fig. 1. Block dimensions and inner/outer diameter of CuCrZr tube for each studied concept (interlayer represented in yellow).

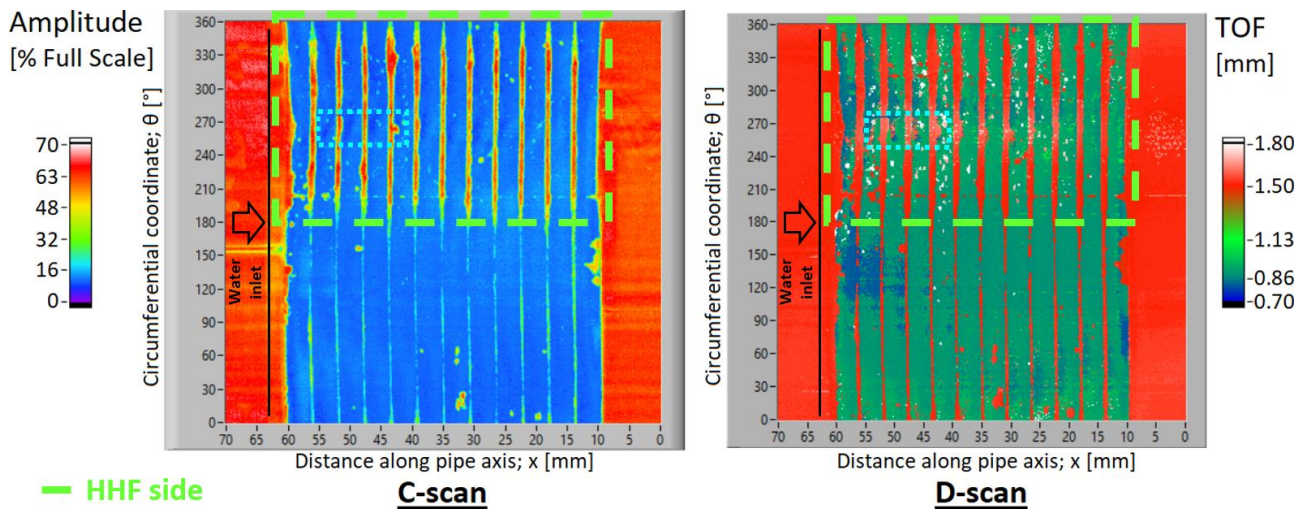


Fig. 2. Scans of the IL mock-up after HHFT. $\Delta TOF = 0.80 - 1.83$ mm ($v = 5000$ m/s); around CuCrZr/interlayer interface. C-scan: blue colour corresponds to good bonding; green to red is for an indication of a defect (debonding at sides of blocks in HHF region, spots). D-scan: In red are all signals measured at the depth of the CuCrZr/interlayer interface (at 1.5 mm); white spots represent porosity inside the interlayer (at ~ 1.8 mm) which is almost entirely localized in the HHF region. In light blue dashed rectangle are the defects also showed in Fig. 5.

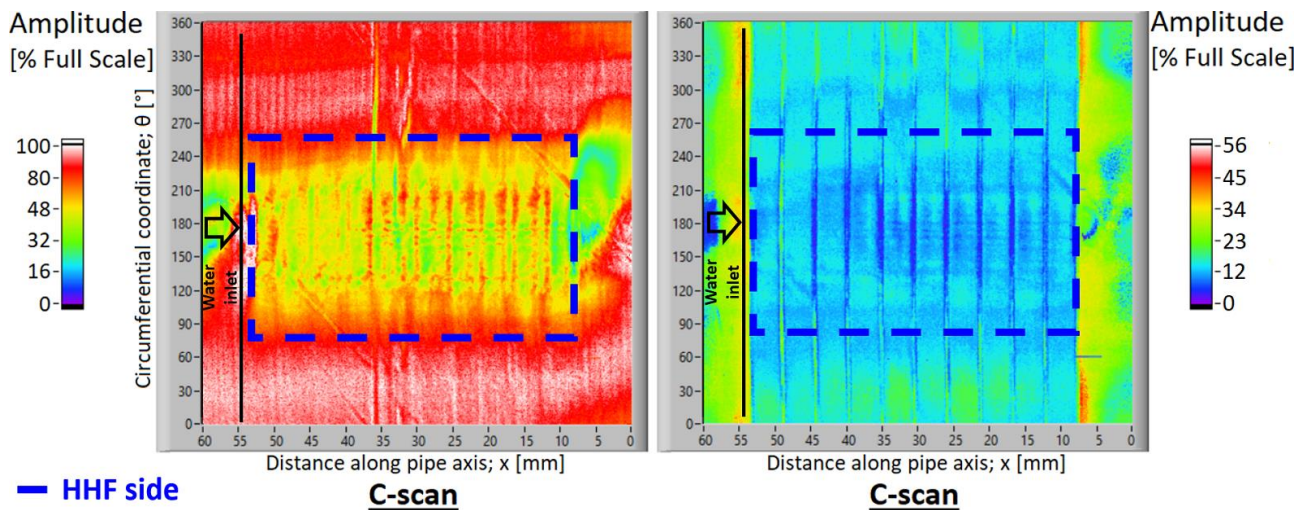


Fig. 3. C-scans of the TGI mock-up after HHFT. Left: $\Delta TOF = 0.00 - 0.40$ mm ($v = 5000$ m/s); water/CuCrZr interface. Modification of pipe inner surface in HHF region. Right: $\Delta TOF = 0.90 - 1.15$ mm ($v = 5000$ m/s); HIP interface. No defects.

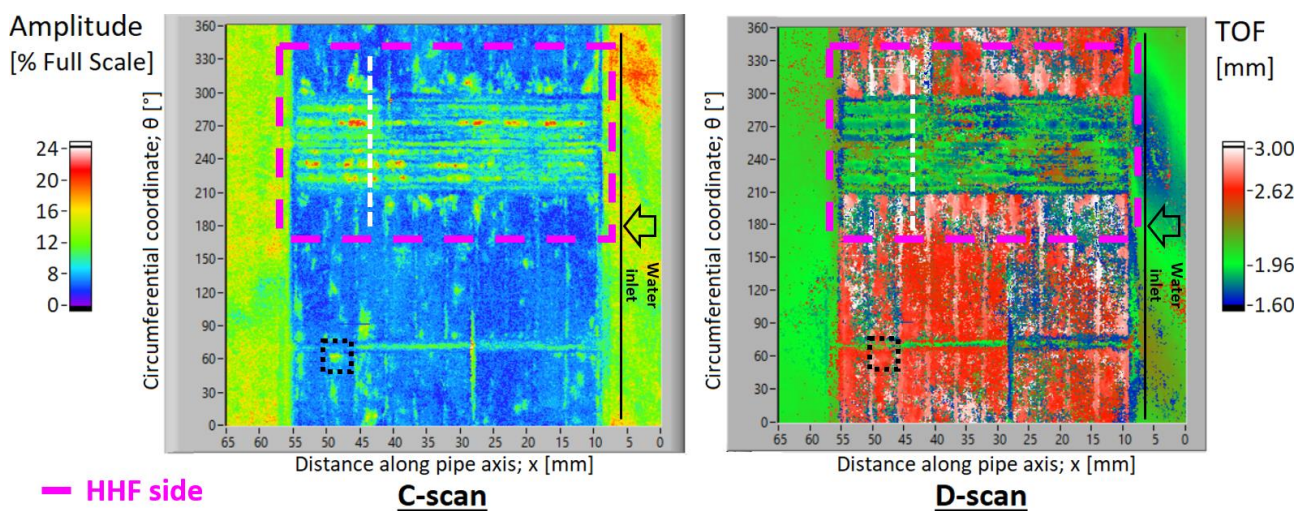


Fig. 4. Scans of the TBI mock-up after HHFT. $\Delta TOF = 1.65 - 3.30$ mm ($v = 5000$ m/s); interlayer/block interface. C-scan: blue colour represents good bonding; green/red is for indication of defects (failure of spokes, porosity, debonding at sides of spokes region); lateral green bands refer to naked pipe. D-scan: blue to green is for a depth inside interlayer (1.60 – 1.96 mm); red to white is for indications at the second Cu-to-Cu brazing interface (2.62 – 3.00 mm). In black dashed rectangle is the defect at 2nd brazing int. showed in Fig. 7 (left). The dashed white line $x = 43$ mm; $\Delta\theta = 175^\circ - 335^\circ$ refers to the B-scans in Fig. 6.

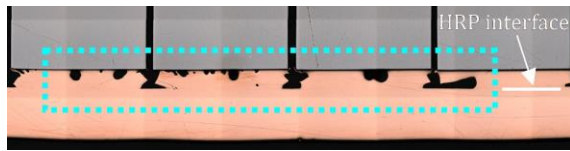


Fig. 5. Defects at blocks 2 to 5 at HHF region (see Fig.2)

of the HIP interface, probably due to its small thickness. In figure 3 (left) the C-scan at the interface between water and CuCrZr shows the morphology of the inner surface of the pipe. We observe an apparent roughening of the surface at the HHF side of the component. From the sole ultrasound test, it is difficult to have a clear interpretation of this measurement. A possible speculation is that it could be a corrosion pattern of the CuCrZr due to the DEMO-relevant hydraulic condition. In the same region, we also observe a mild thickening of the tube of about $\sim 150 \mu\text{m}$ (not shown in scans). This could be related to plastic deformation or to some defects inside the pipe that ultrasound cannot detect (e.g. microporosity). Further study is then required, as for example destructive metallographic analyses (ongoing). A similar indication, of both the pattern and the thickening of the tube plus interlayer thickness, is detected also in the IL mock-up, but not in the one with TBI.

The scans of the mock-up with TBI (Fig. 4) are reported at a ΔTOF that contains the interface between the Cu interlayer and the W block (2nd brazing interface). In the C-scan, we identify three main critical features. The first is the indications from the copper radial spokes (coloured green to red; C-scan). The morphology of these defects is difficult to determine due to the complex geometry of the sample. However, this indication was not present before HHF tests, as show in the B-scans in Fig. 6, and therefore we are confident that, in large part, the spokes were interrupted due to thermal fatigue cycling. Second type of defect that appeared after HHF tests, is a debonding between the Cu interlayer and W block, which is localized at the sides of the spokes region. In the C-scan this appears as yellow/green spots at $185^\circ < \theta < 200^\circ$; $290^\circ < \theta < 330^\circ$. This is the region of the component where the heat flux would intensify if no flux were exhausted through the spokes. The last defects consist of porosity at the second Cu/Cu interface, represented as distributed green spots in the C-scan. Some pores were present before HHF tests, but the majority was generated during the thermal cycles. The indications inside the spokes appear in the D-scan at a depth from 1.60 to 1.96 mm (green/blue), while all other defects are detected between 2.62 and 3.00 mm (red/white; 2nd brazing interface). Preliminary post-mortem analysis confirms UT results by showing porosity at the second brazing interface (Fig. 7) and failure of the copper spokes. For the defects near the spoke region dedicated cuts are yet to be performed.

4. Conclusions

A comparison between three water-cooled W-monoblock concepts has been performed. UT results for the different designs have been analysed before and after HHF tests. After thermal fatigue, the IL mock-up shows debonding at the sides of each block in the HHF region at the HRP interface. Manufacturing defects at the same

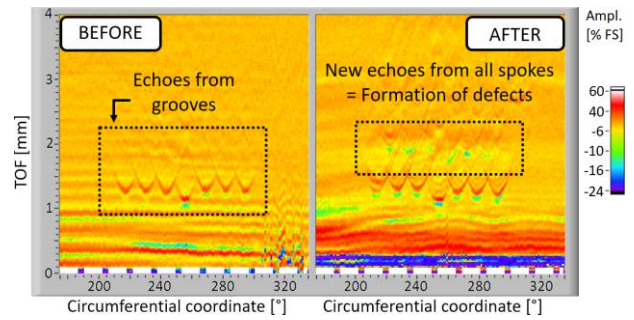


Fig. 6. B-scan before and after HHF tests along the dashed white line in Fig.4.

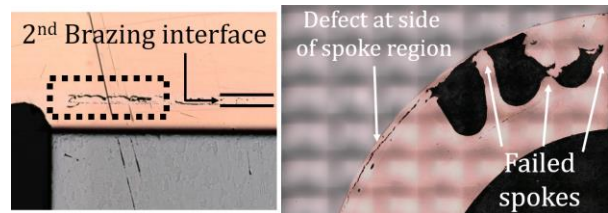


Fig. 7. (TBI) Left: Defect at block 9 at low flux side (see Fig. 4). Right: Defects in the right half of block 8.

interface did not increase their dimension after HHF tests. Porosity was detected in the casted Cu interlayer and increased in size at the HHF region after loading. The mock-up with the TGI showed no debonding at the HIP interface as well as no failure of the graded material. For both IL and TGI samples (and not for the TBI one), modification of the inner surface of the pipe was detected on the HHF side after thermal fatigue tests, as well as an increased thickness ($\sim 150 \mu\text{m}$) of the pipe in the same region. In the mock-up with the TBI, failures of the copper spokes are detected after HHF tests. In addition, localized debonding at the second Cu-to-Cu brazing interface appeared near the spokes region. Increased porosity is diffusely detected at the same interface as spread spots in the whole mock-up. Preliminary post-mortem analysis proves the UT capability in imaging defects with accuracy also for advanced W-monoblock divertor concepts.

Acknowledgments

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